Firming Renewable Power with Demand Response: An End to End Aggregator Business Model

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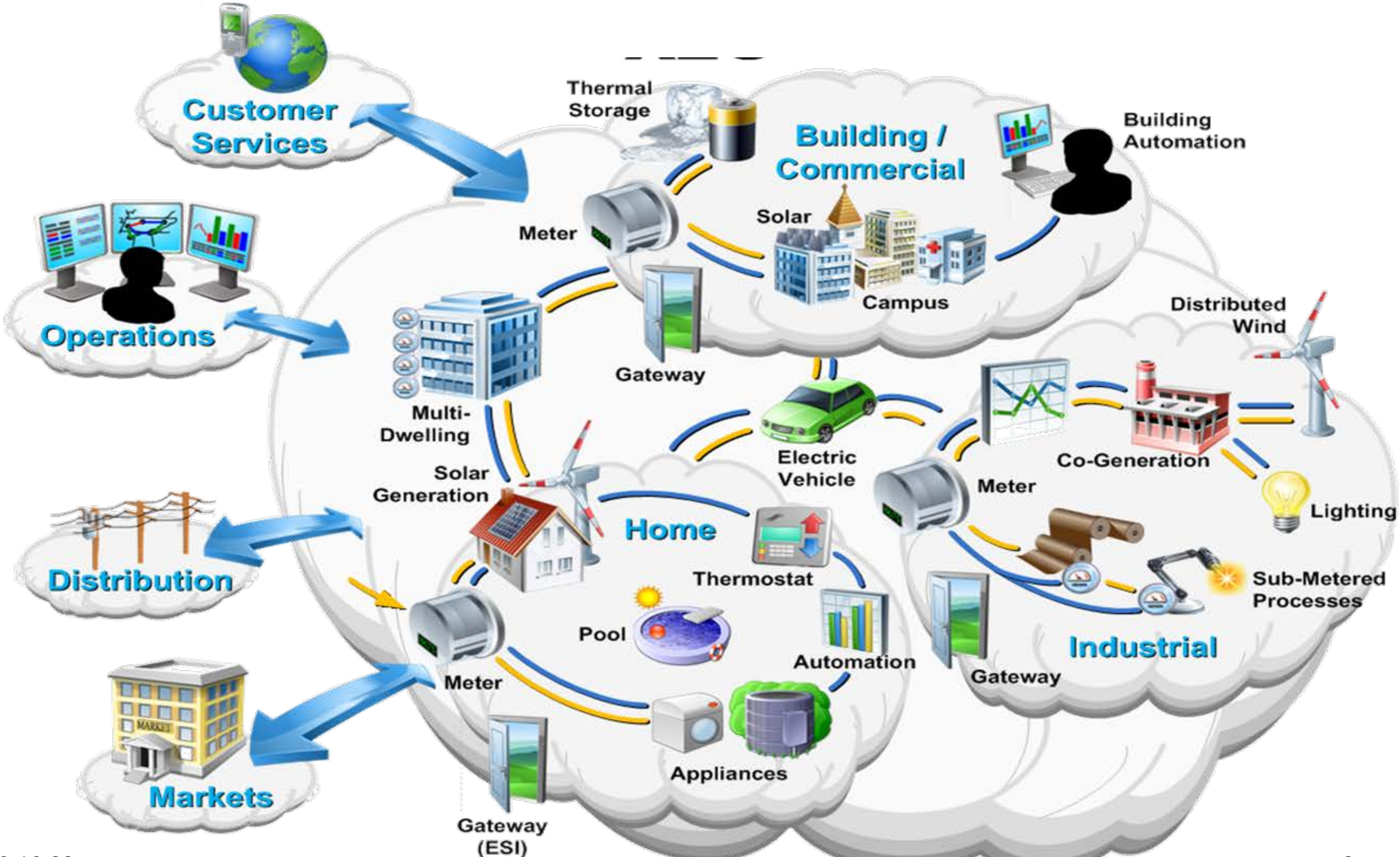
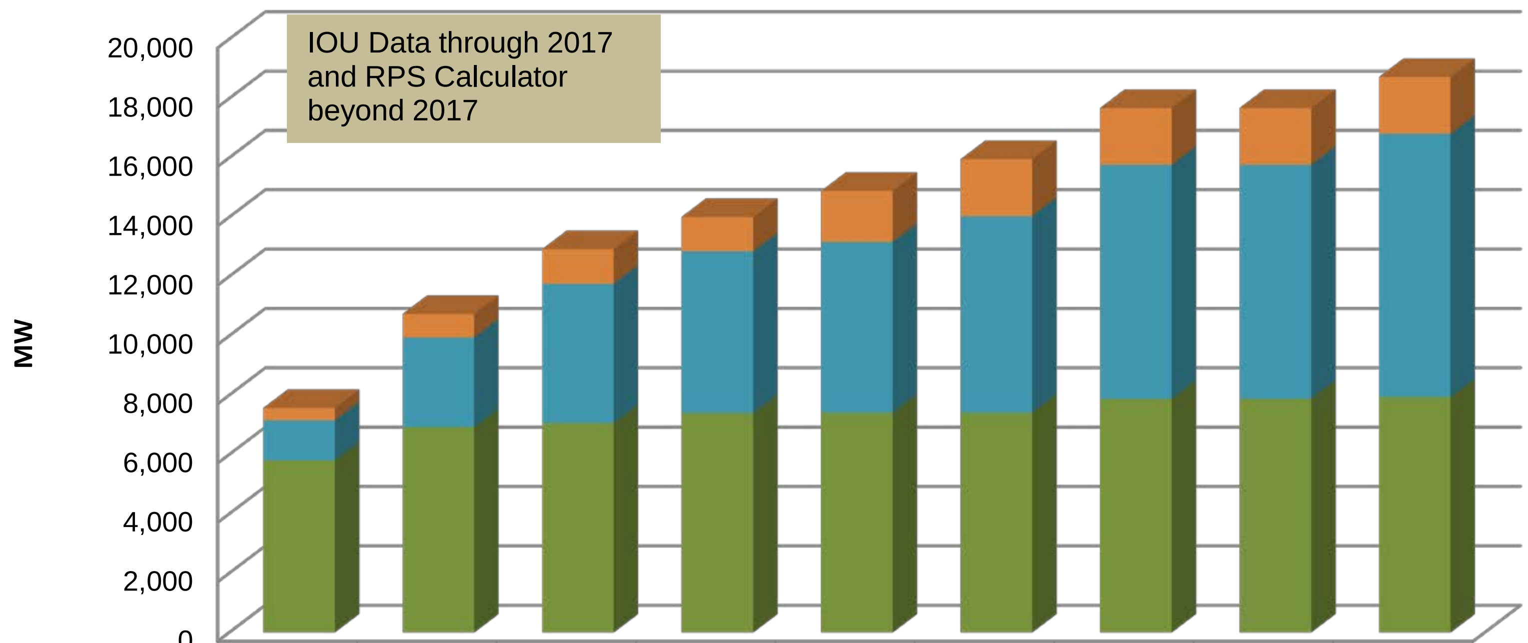
Future Electricity System



33% RPS - Cumulative expected VERs build-out through 2020

33% RPS --- Variable Resources Expected Build-out Through 2020

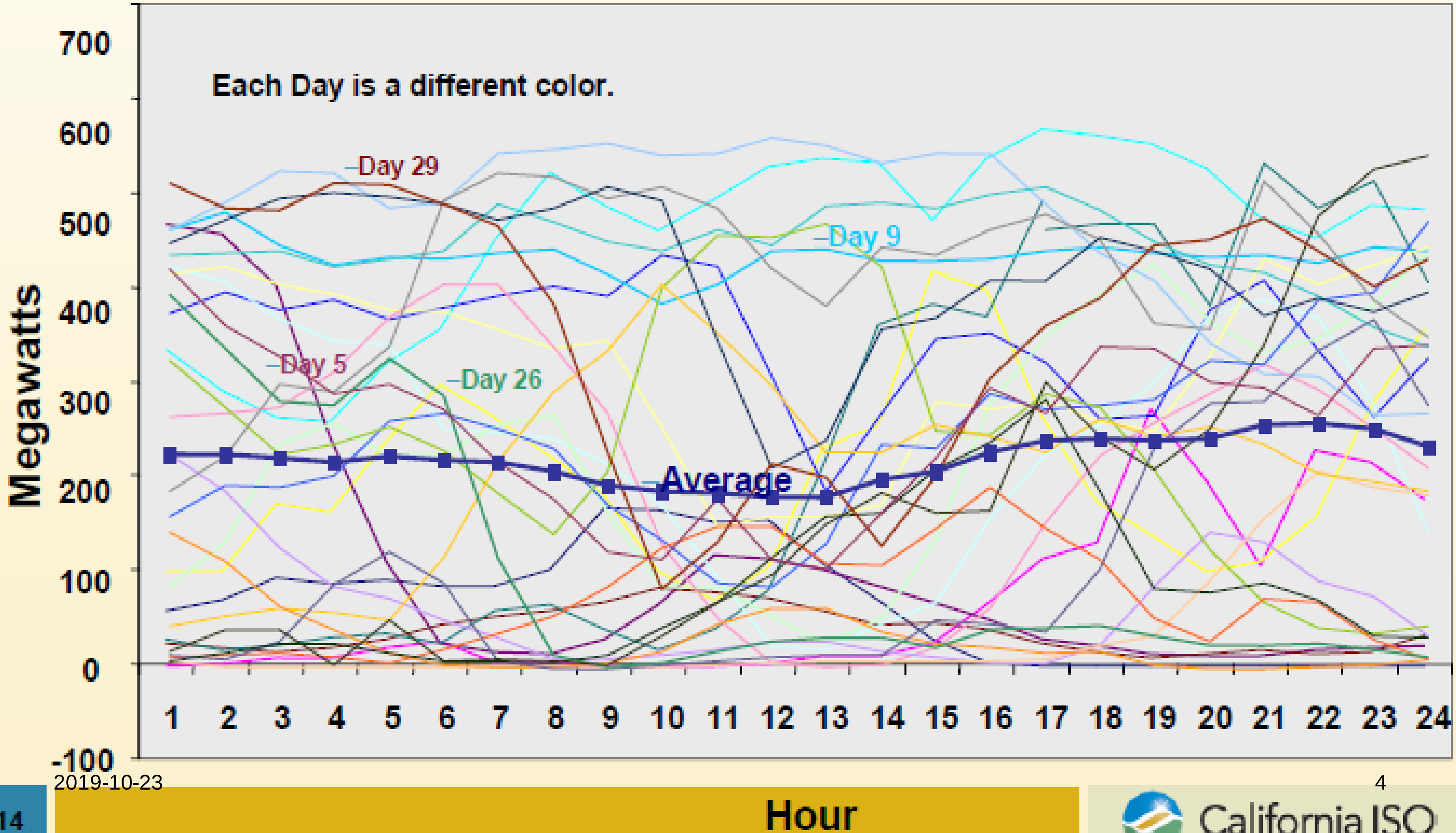


	2012 Existing	2013	2014	2015	2016	2017	2018	2019	2020
Solar Thermal	419	792	1,167	1,167	1,717	1,917	1,917	1,917	1,917
Solar PV	1,345	3,022	4,693	5,445	5,756	6,628	7,881	7,881	8,872
Wind	5,800	6,922	7,058	7,396	7,406	7,406	7,877	7,877	7,934

Source: CAISO

Tehachapi Wind Generation in April – 2005

Could you predict the energy production for this wind park either day-ahead or 5 hours in advance?



Negative Correlation with Load

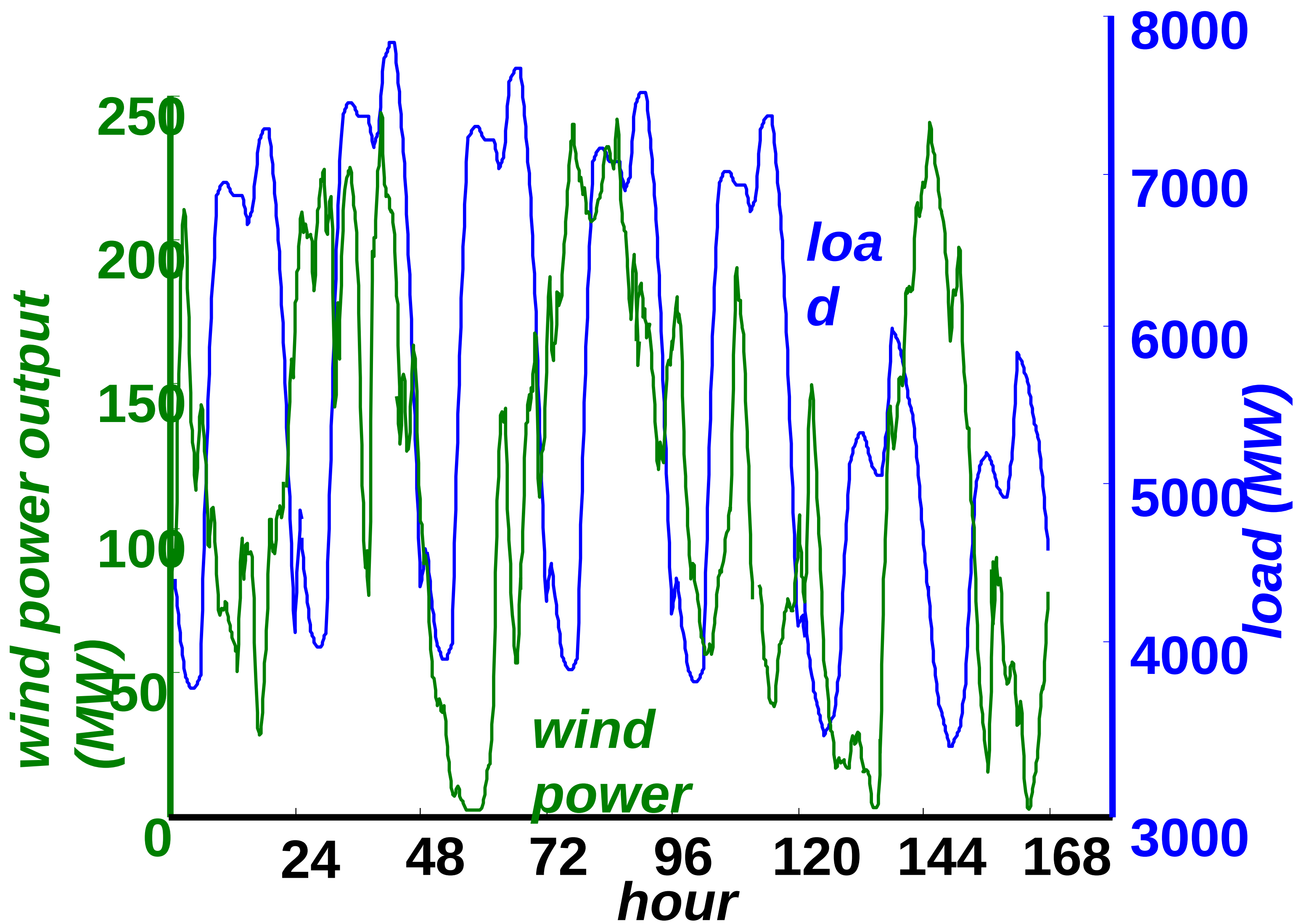
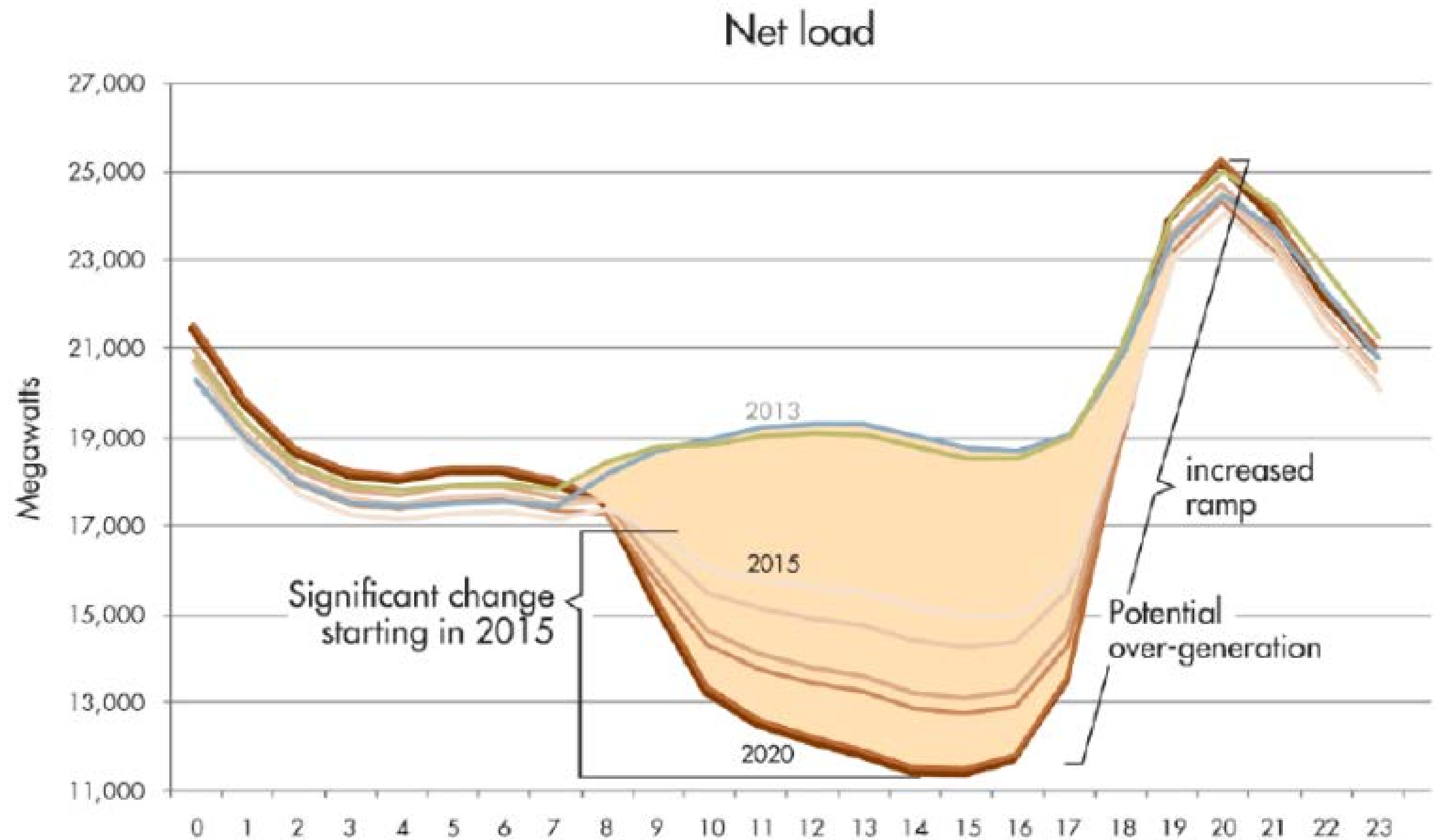


Chart 1: CAISO' Projected Net Load by Hour, using Avg. Projected Usage (aka "Duck Chart")

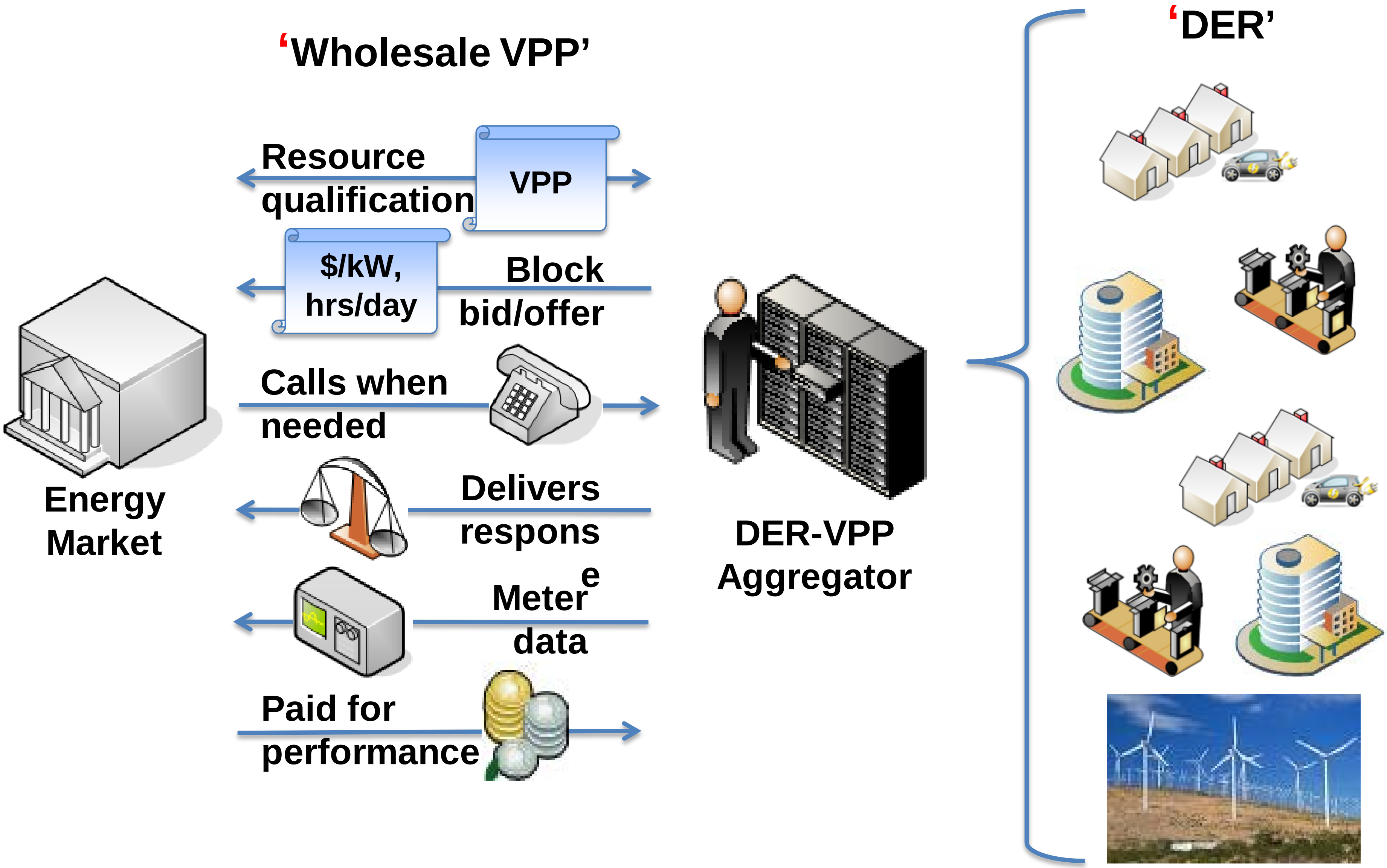


Source: CAISO

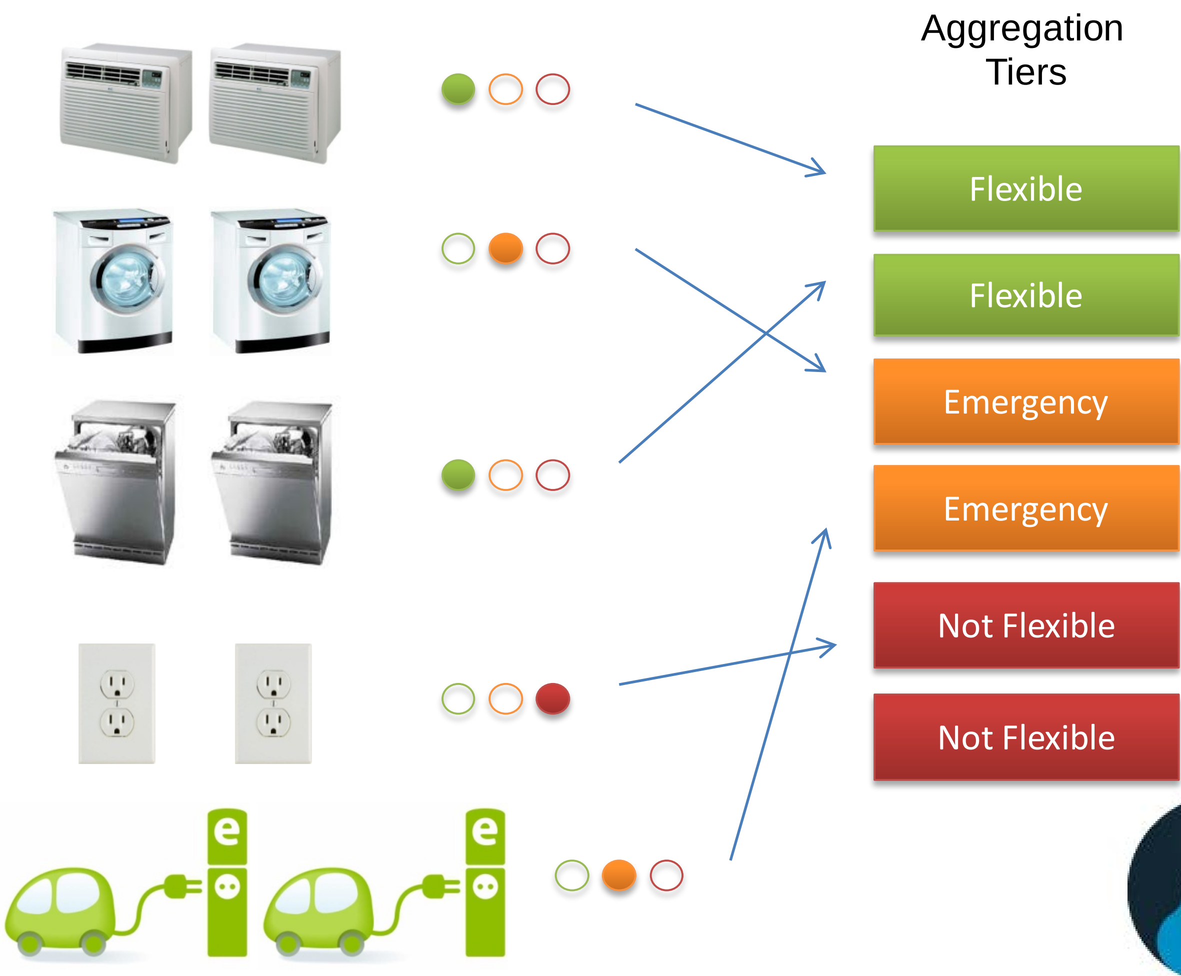
Key Challenges and Solutions

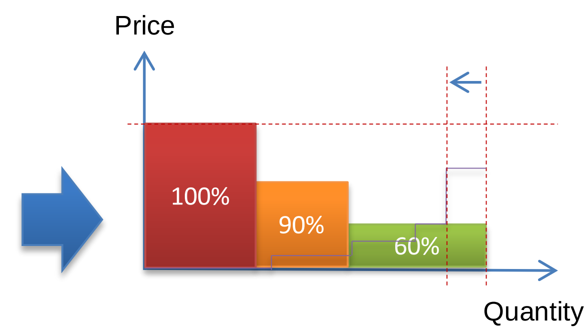
- Challenges:
  - Proliferation of distributed energy resources
  - Uncertainty and variability of renewable resources
- Solutions:
  - Add flexible generation capacity
  - Market design to incentivize resource flexibility (through investment and operation)
  - Smart grid technologies and storage
  - Mobilize demand response

DER Aggregation through Virtual Power Plants

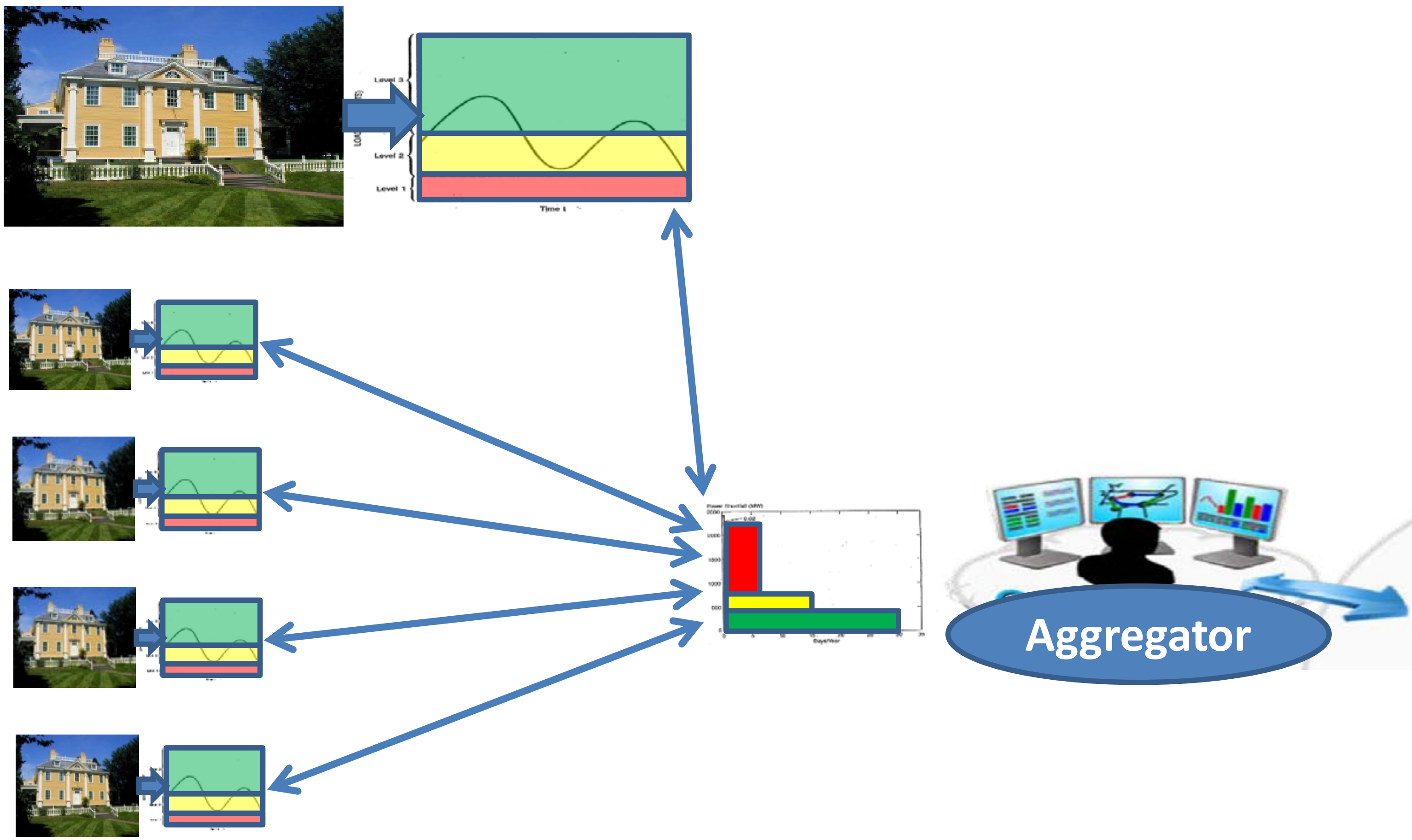


Device Control Paradigm





Fuse [capacity] Control Paradigm
(customer controls allocation of curtailed capacity)



Southern California Edison Company

Fishing for a way to reduce the cost of your electric service?

Southern California Edison Company

Interruptible Schedules

Monthly Billing Credits	I-2	I-3	I-4
10-minute rate	$3.10/kW	$1.50/kW	$1.00/kW
30-minute rate	2.60/kW	1.00/kW	.50/kW
2-hour rate	—	.50/kW	.00/kW
Additional if interrupted during month		3.00/kW	2.50/kW

The number of periods of interruption will not exceed an average of 15 times or 180 hours per calendar year over a five-year period (except for Schedule I-4, which is for one year).

Offered to commercial and industrial customers with load > 500KW

"GET CREDIT FOR TAKING TIME OFF."

YES, I'LL TAKE THE CREDIT.

Put the peel-off address label here.

An Edison representative will phone to make arrangements to install the device. Please be sure to include your home or work phone number below:

(____) ____________________ home/work

Best time to contact me is: ______ a.m./p.m.

Please complete the following and check appropriate boxes. Tear off and return.

☐ I am an Edison residential customer with electric central air conditioning. Please put me on the new rate schedule D-APS 2 (Air Conditioner Cycling). I have read the brochure information regarding this rate.

Install a device on my air conditioning equipment for the savings option checked below so that I will receive a credit on my bill each month during the 6 summer months.

☐ A—$5.50 credit for each ton of my air conditioner

☐ B—$3.00 credit for each ton of my air conditioner

☐ C—$1.50 credit for each ton of my air conditioner

☐ I am interested but would like additional information about this program.

____

Signature of owner/manager, if approval needed.

"Read this. I'd like to see you get up to $165 just by signing up for Air Conditioner Cycling."

—George Burns

If you have central air conditioning, you can save money on your summer electric bills by participating in the Air Conditioner Cycling Program.

This program helps slow the growing demand for new power plants. When business and industry are in full production and residential customers are using electrical appliances and air conditioners, the demand for electricity reaches peak levels. Air Conditioner Cycling helps manage the growth of peaks and reduces the need to build new power plants.

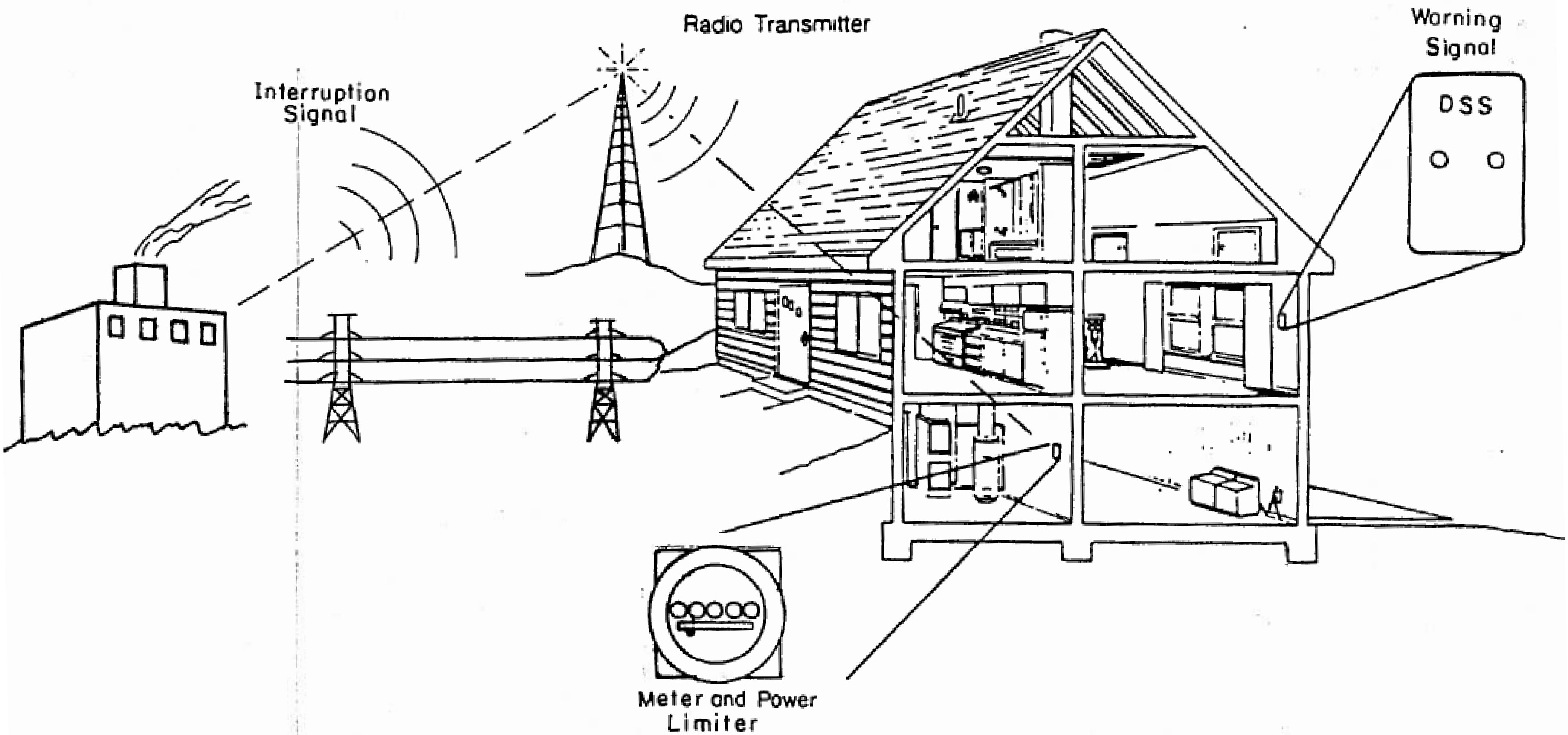
Here's how the program works.

By choosing to participate in the new Air Conditioner Cycling Program, you'll get a credit toward your

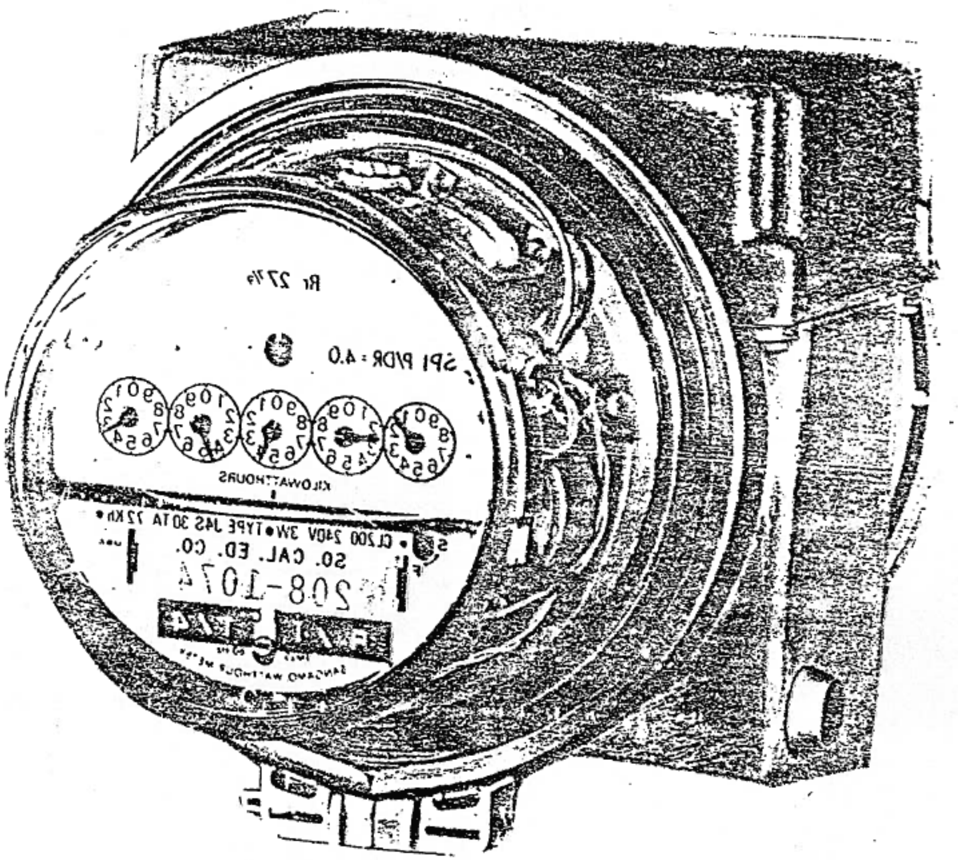
THERE ARE THREE SAVINGS OPTIONS.	**EXAMPLES***	TOTAL SAVINGS OVER 6 SUMMER MONTHS.					
SAVINGS OPTION	MONTHLY SAVINGS FOR EACH TON OF A/C	2.5-TON UNIT	3-TON UNIT	3.5-TON UNIT	4-TON UNIT	4.5-TON UNIT	5-TON UNIT
A—off full time cycling is in effect	$5.50	$82.50	$99	$115.50	$132	$148.50	$165
B—off 10 min. out of each 15 min. period	$3.00	$45	$54	$63	$72	$81	$90
C—off 7½ min. out of each 15 min. period	$1.50	$22.50	$27	$31.50	$36	$40.50	$45

*Any size electric central air conditioner or heat pump in good working condition qualifies for this program.

Demand Subscription Service
(implemented at SCE in the early 1980's)

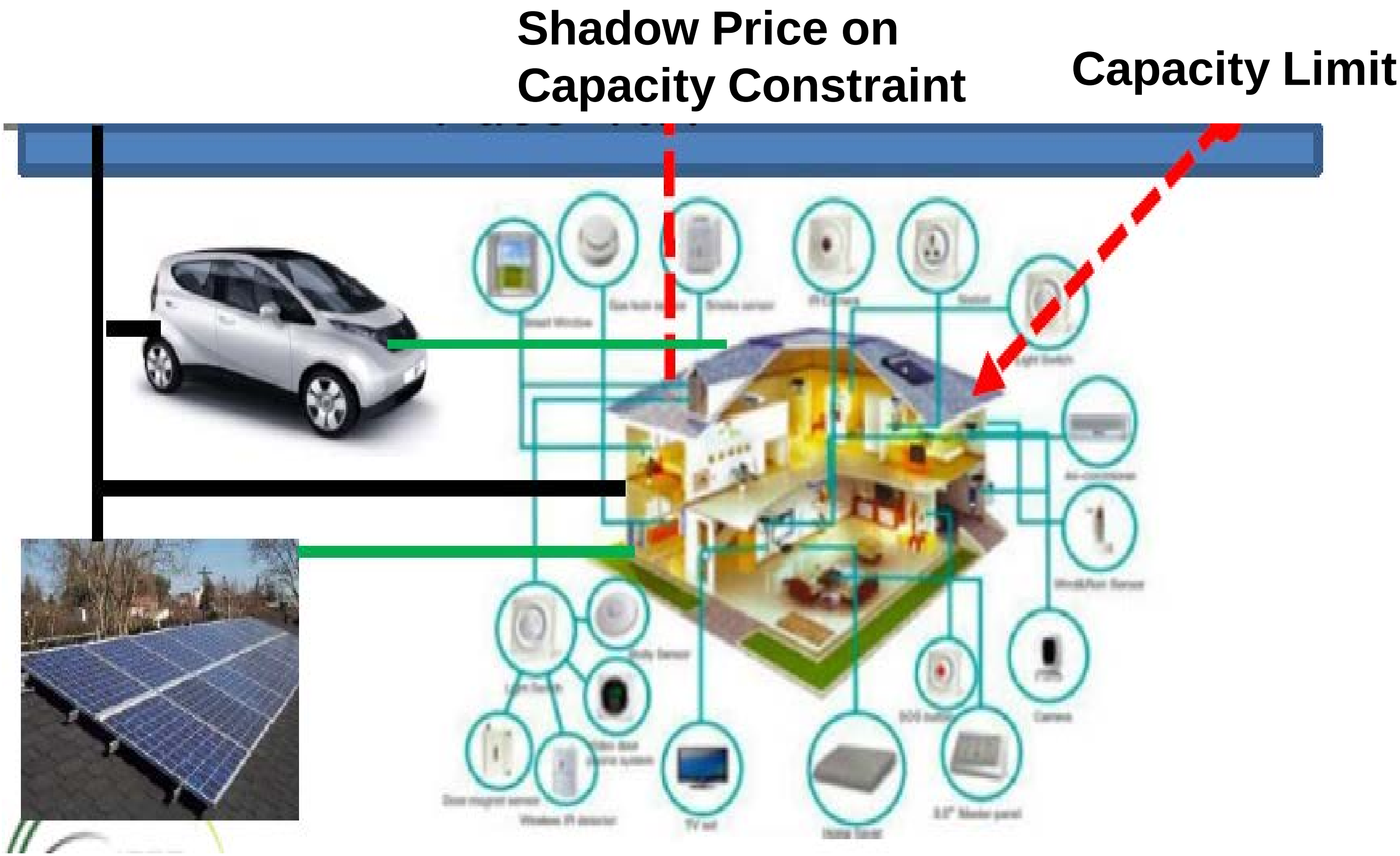


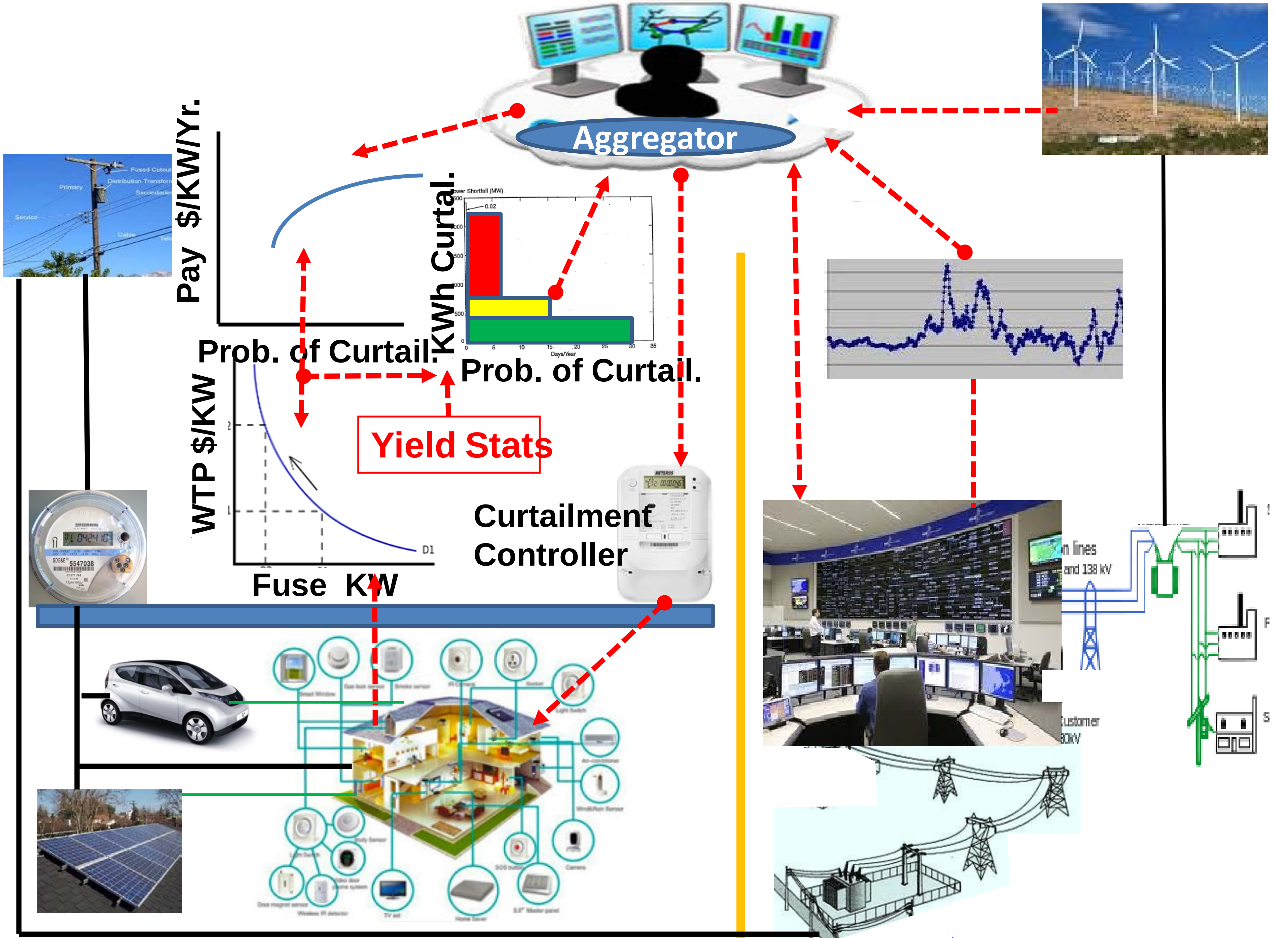
Demand Subscription Service: Radio controlled fuse limits customer's power supply to his subscribed level.


SO. CAL. ED. CO.


DSS TM SM
DEMAND SUBSCRIPTION SERVICE TM SM
ACTIVATED
SELECTED LEVEL EXCEEDED
SOUTHERN CALIFORNIA EDISON COMPANY

Autonomous Capacity Constrained Energy Management





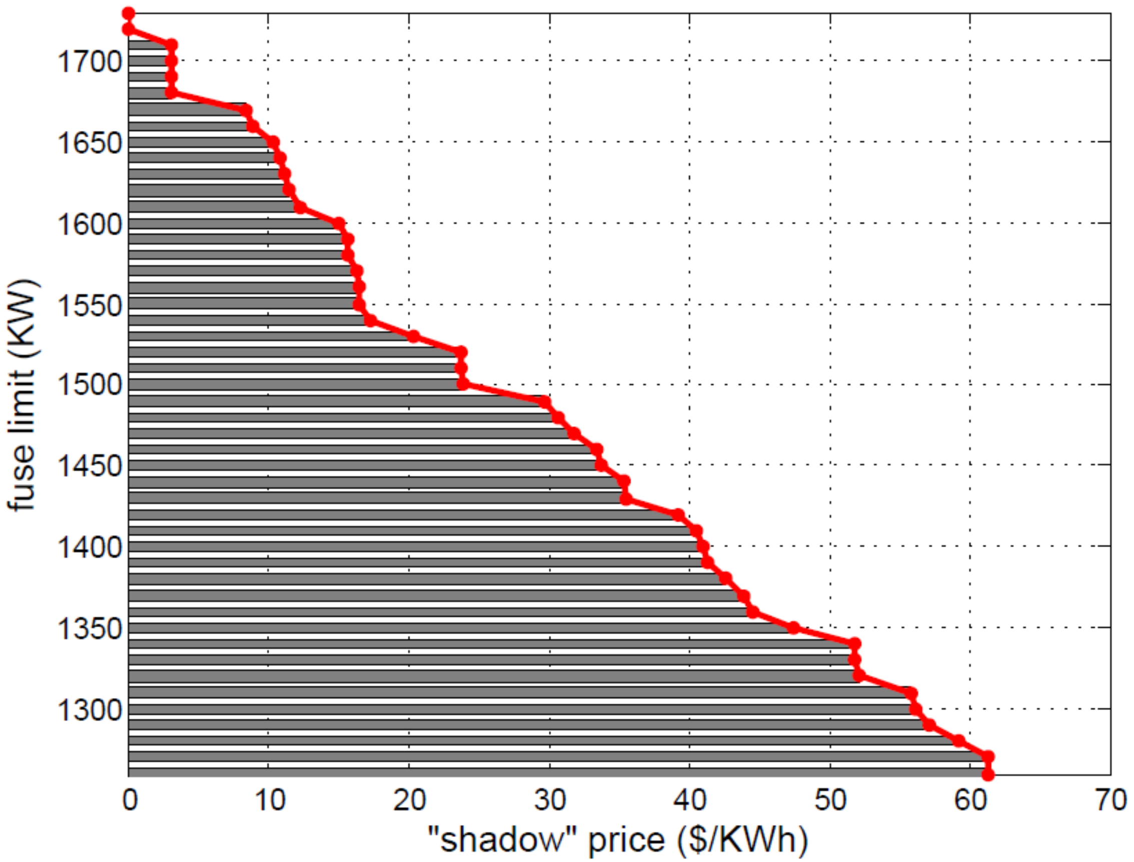
Aggregator
Pay $/KW/Yr.
Prob. of Curtail.
KWh Curtal.
Prob. of Curtail.
WTP $/KW
Fuse KW
Yield Stats
Curtailment
Controller

Regulatory Framework Will Change to Eliminate Subsidies

- Renewable resources must have incentives to firm up their supply.
  - Renewable should bear the cost of production uncertainty and variability
  - Eliminate feed-in tariffs and require renewables to schedule (at least in the 15 minute market)
  - Enable firmed up renewable resources (bundled with flexible load) to receive capacity payments
- Demand should have incentives to bear supply risk along with self-supply of energy.
  - Eliminate net metering and replace pure volumetric charges with two part tariffs (energy and connection charges).
  - Enable quality of service differentiation through differential connection charges

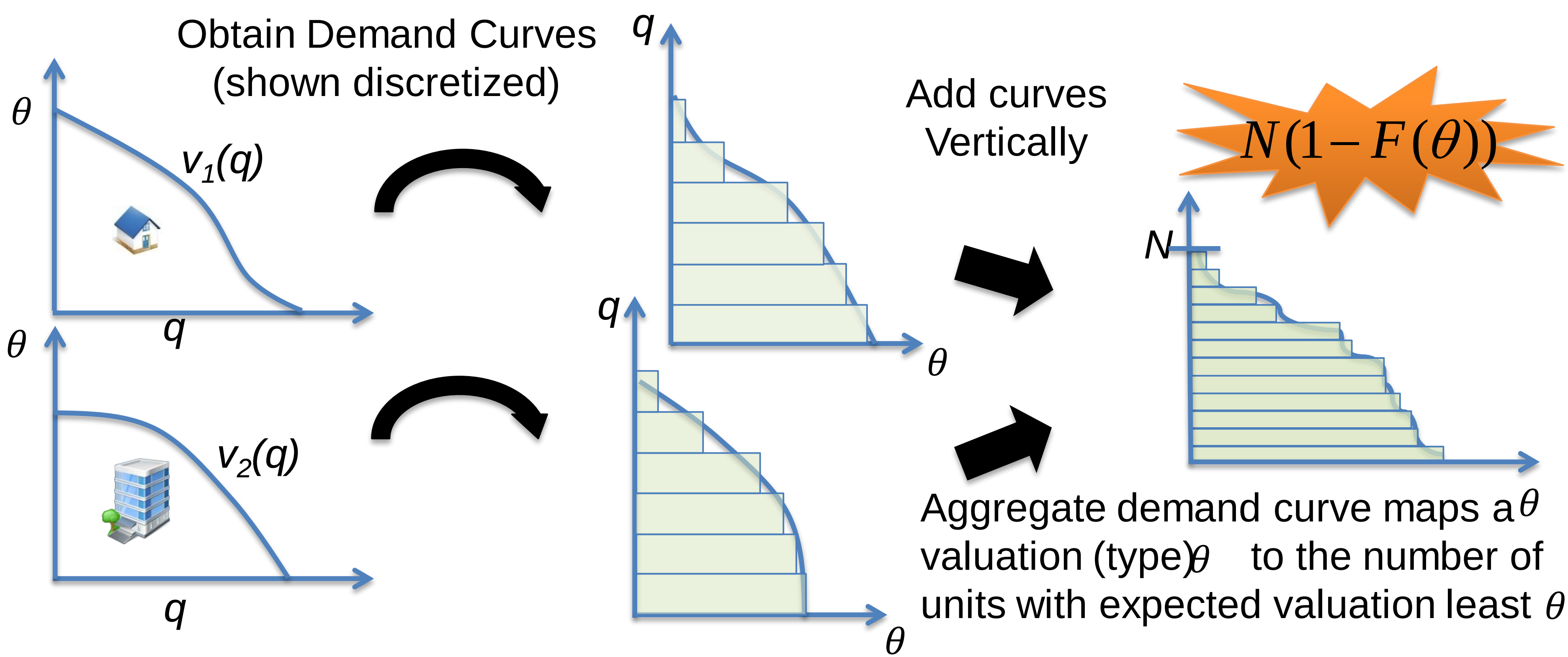
Fuse increment offer curve

House hold energy management probem subject to a capacity limit produces a shadow price on incremental capacity (fuse) which can be interpreted as a household demand function for fuse capacity or an offer curve for incremental capacity curtailment.



The Customer Model

DR customers are represented in aggregate as a continuum of demand increments, each with an expected valuation θ (referred to as type). The aggregate demand curve is the CDF of types scaled to total load capacity *N*, $D(\theta) = N(1 - F(\theta))$

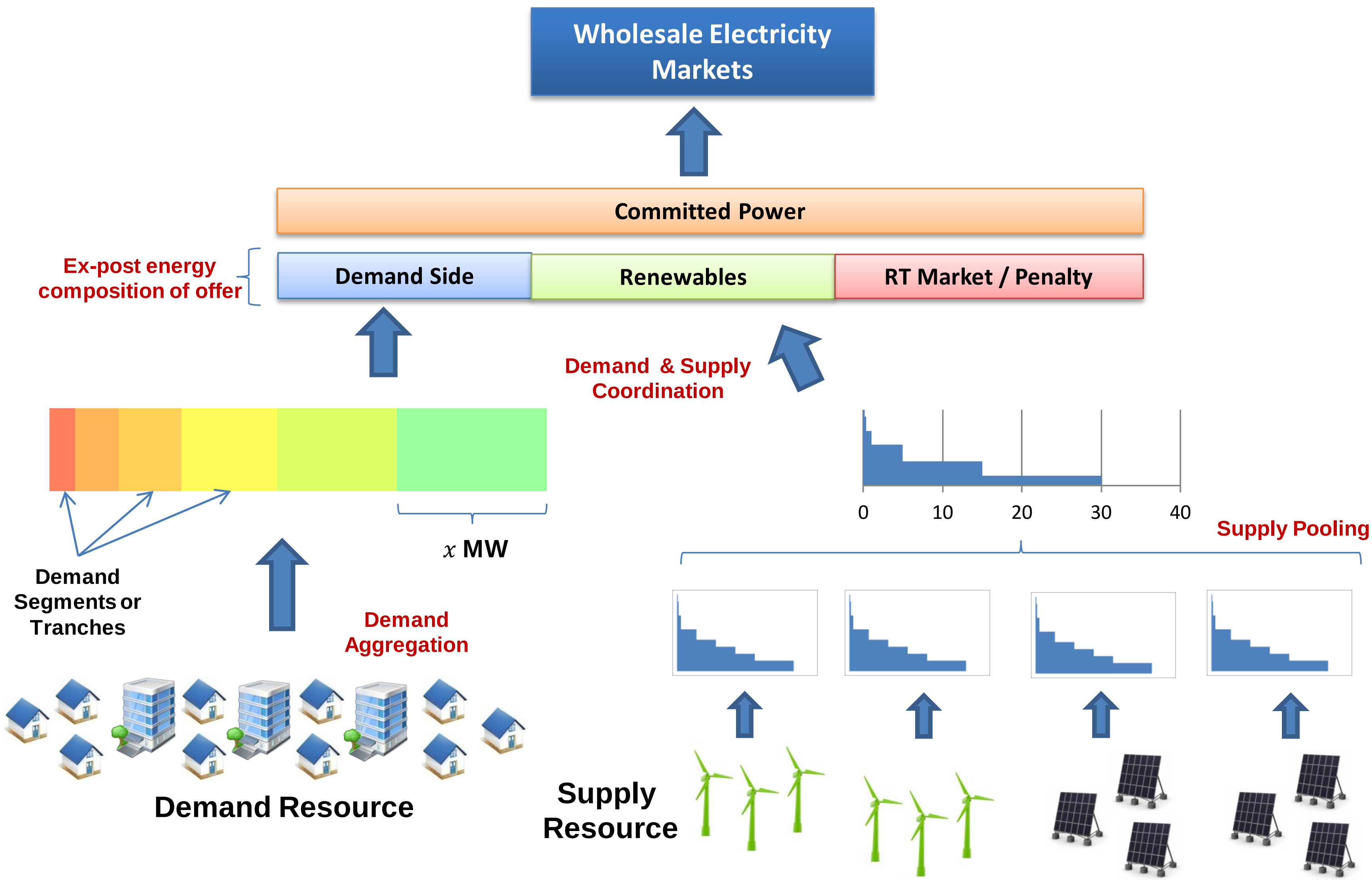


Aggregate demand curve maps a valuation (type) θ to the number of units with expected valuation least θ

The "Customer" Model (for each load segment)

- "Customer" values a unit of consumption at θ and faces retail rate p^R
  - ➡"Outside option" utility = $(\theta - p^R)^+$. (forgo contract)
- Pay load segment $t(\theta)$ for the right to curtail this segment with probability $1 - r(\theta)$.
- Customers are risk-neutral:
  - ➡utility with contract = $r(\theta - p^R)^+ + t(\theta)$,

The Wholesale Product Offered by the Aggregator



The Aggregator’s Operations

- Aggregator owns a variable energy resource, producing power quantity s with pdf $g(s)$
- Offers a menu of contracts to capacity increments with ex-ante payments that vary with customer self-selected probability of curtailment for each increment and pays
- Commits to supply power quantity q in the forward wholesale market contingent on the whole sale price p
- After observing variable energy realization, dispatches a scenario-dependent quantity of contracted DR
- Collects a net settlement

$$pq + a\left[DR + s - q\right]^{+} + b\left[DR + s - q\right]^{-}$$

The Aggregator's Problem

$$\max_{q,DR,T} \bar{J}(q, DR, T)$$

$$= \max_{q,DR,T} \mathbb{E}_{p,a,b,s}\Big[\underset{\substack{\uparrow \\ \text{Day-ahead revenue}}}{p\,q} + a(\overbrace{DR + s - q}^{\text{overproduction}})^+ - b(\overbrace{q - DR - s}^{\text{shortfall}})^+\Big] - \underset{\substack{\uparrow \\ \text{payment to DR}}}{T}$$

- Random variables
  - p : day ahead (DA) price
  - a : overproduction payment rate
  - b : shortfall penalty rate
  - s : Real time (RT) VER realization, "wind", $\sim g(\cdot)$
- Control policy variables
  - q : $(p, a, b) \mapsto q(p, a, b) \geq 0$: DA offer quantity
  - DR : $(p, a, b, s) \mapsto DR(p, a, b, s) \geq 0$: DR dispatch quantity
  - T is determined by DR, using contract theory, explained below

DR Curtailment Contract Example

	Customer Type								Total MW	Interruption Cost ($/kW)/Day
	1	2	3	4	5	6	7	8		
MW of Demand	100	—	—	100	—	—	—	—	200	200
	—	—	100	100	100	100	—	—	400	50
	100	100	100	—	—	100	100	100	600	10
	—	100	—	100	100	—	100	100	500	3
	—	100	100	—	—	100	—	100	400	1
	100	—	—	—	100	—	100	—	300	0.5

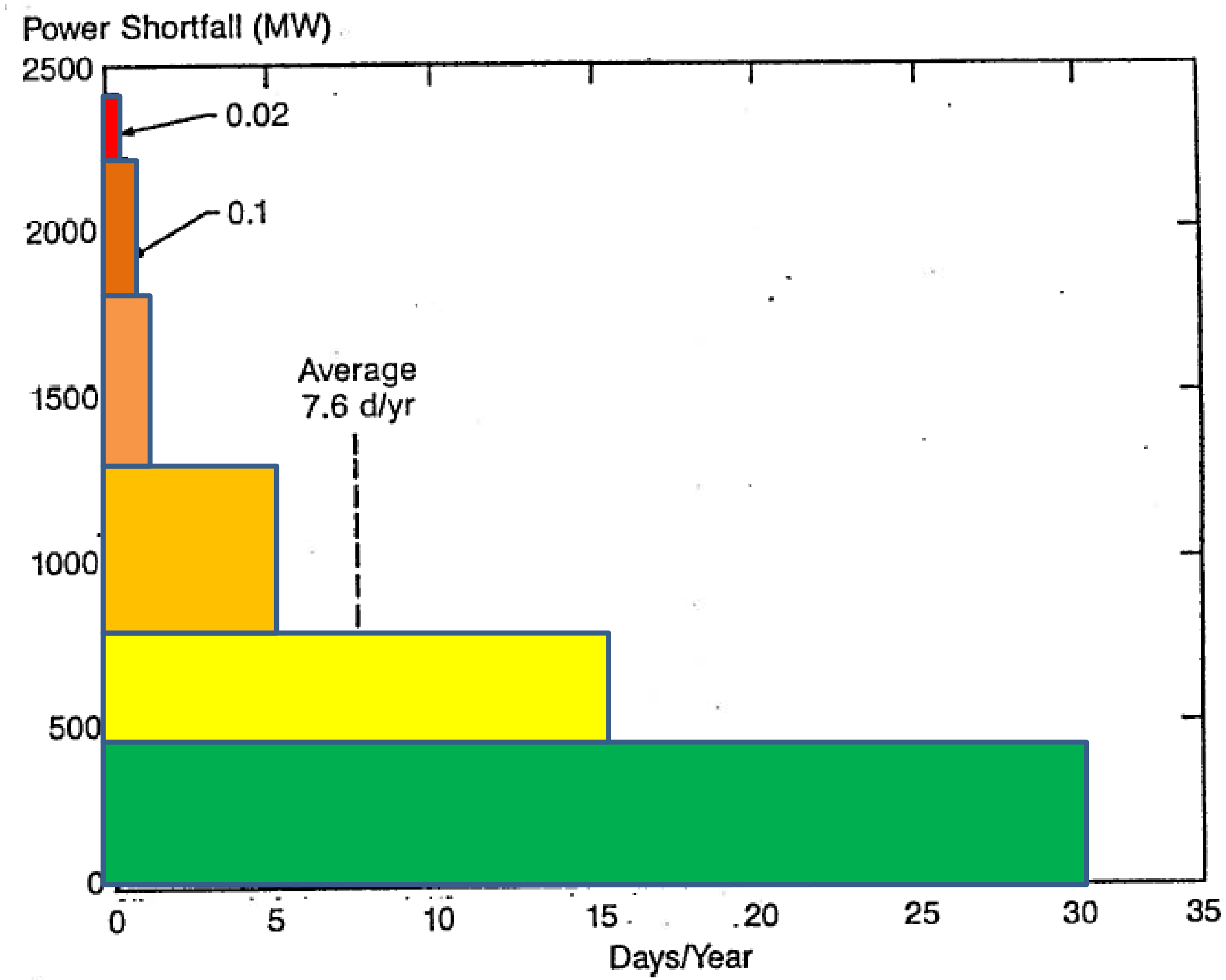
Only the last two columns characterizing the shortage cost histogram in the population are needed for price menu design

Contract Structure

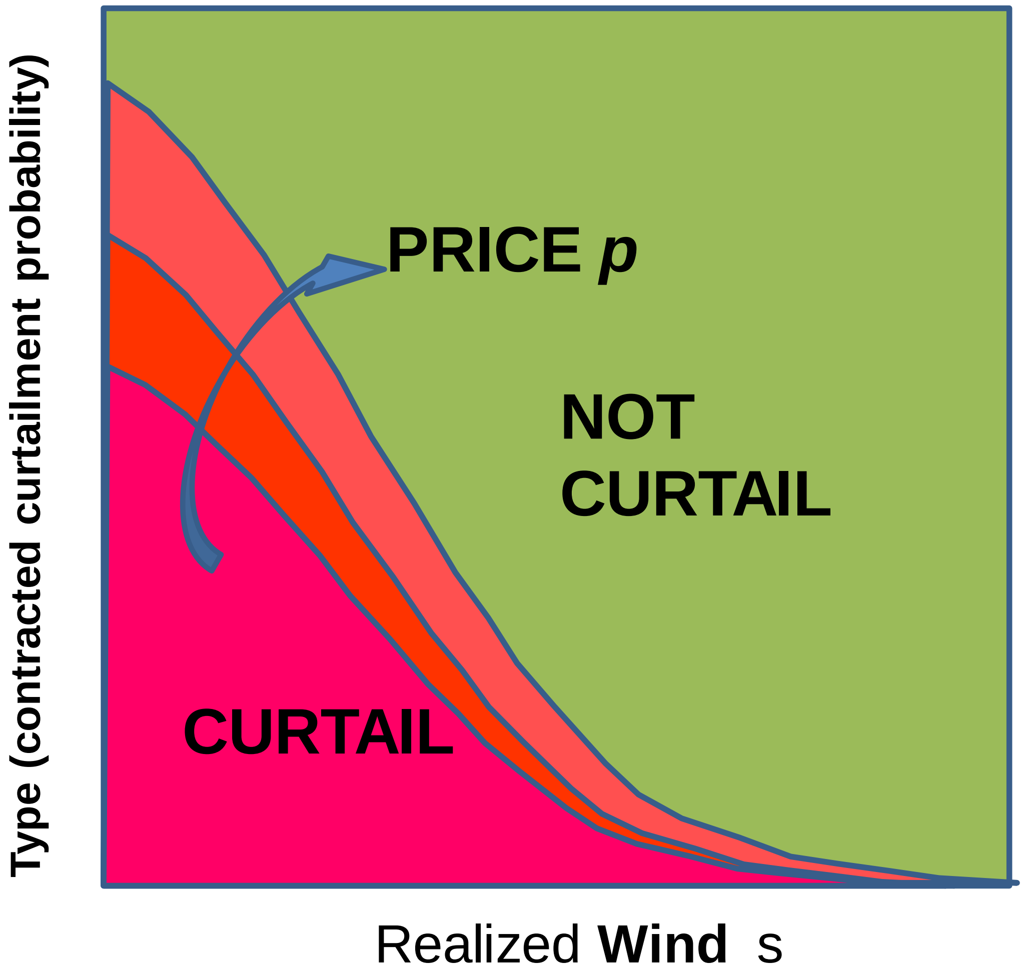
	Average Number of Days/Year Interrupted					
	0.02	*0.1*	*1*	*5*	*15*	*30*
Net Connection Charge $/Kw/Yr	84	72	48	30	12	0

- Each customer type minimizes service charge + expected interruption cost
- Menu prices are designed to induce appropriate customer selections

Supply Shortfall Profile = Load Curtailment Profile



DR Curtailment Policy



DR Contract Design

Contract theory: “direct revelation mechanism”

- Increment’s ex ante valuation without curtailment: $z(\theta) \triangleq \mathbb{E}_\epsilon[\theta + \epsilon - R]^+$
- DR yield per unit curtailed $= \frac{\mathrm{d}}{\mathrm{d}\theta} z(\theta) = z'(\theta)$
- Net ex ante valuation with contract: $u(\kappa, \theta) = u_{\mathrm{ref}} - \kappa z(\theta)$
- Calculate probability of curtailment $\kappa(\tilde{\theta})$ and payment $t(\tilde{\theta})$, and offer menu of contracts $\langle \kappa, t \rangle$
- IC: $\theta = \arg\max_{\tilde{\theta}} u(\kappa(\tilde{\theta}), \theta) + t(\tilde{\theta})$. $\Rightarrow \kappa(\theta)$ decreasing; and $t(\theta) = \overline{v} - \int_\theta^{\overline{\theta}} \frac{\partial}{\partial x} u(\kappa(x), x)\, \mathrm{d}x - u(\kappa(\theta), \theta)$, ($\overline{v}$ integ constant)
- IR: $\overline{v} = u(\kappa(\overline{\theta}), \overline{\theta}) + t(\overline{\theta})) - u_{\mathrm{ref}}(\overline{\theta}) = 0$
- This determines payment T as a function of policy $\hat{\theta}(\cdots)$, depending only on $\kappa(\cdot)$.
- $T = \int \Omega(\theta)\kappa(\theta)\, \mathrm{d}F(\theta) = \mathbb{E}_{p,a,b,s}\left[\int \Omega(\theta) \mathbb{1}_{\{\theta \leq \hat{\theta}\}}\, \mathrm{d}F(\theta)\right]$
- $\Omega(\theta) \geq 0$ is marginal cost of increasing $\kappa(\theta)$: “virtual valuation,” determined by F, z, …

Optimizing DR Policy Pointwise

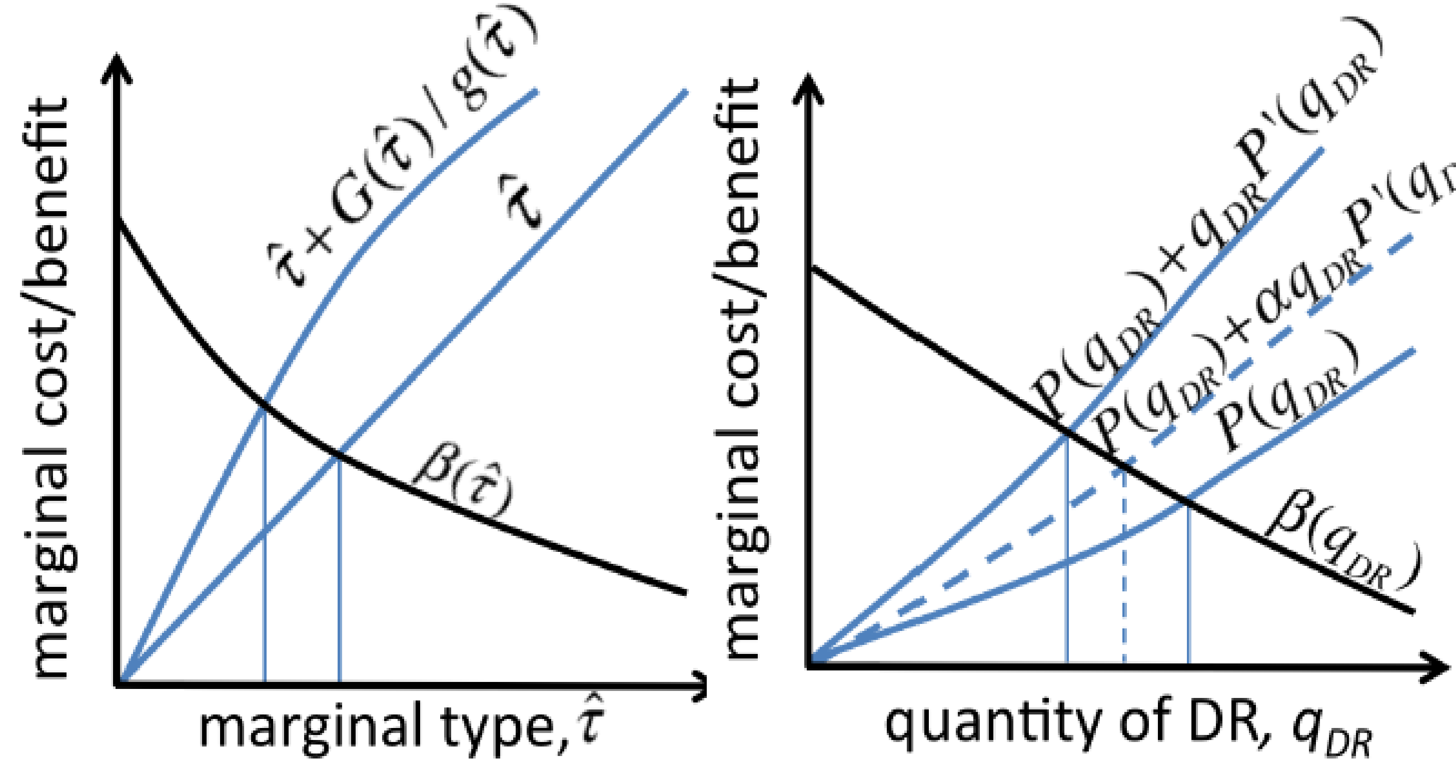
$$\max_{q,\hat{\theta}} \bar{J} = \mathbb{E}_{p,a,b} \max_{q} \mathbb{E}_s \max_{\hat{\theta}} [J(p,a,b,s;\hat{\theta}(\cdot),q(\cdot))]$$

- $\Omega(\theta) =$ cost to curtail type θ (contract theory analysis)
- $z'(\theta) =$ the resulting quantity of DR from a unit mass of type θ
- $MC(\theta) \triangleq \Omega(\theta)/z'(\theta)$: marginal cost per unit DR yield
- $DR(s) \triangleq \int z'(\theta)\mathbb{1}_{\theta \le \hat{\theta}(p,a,b,s)}\, dF(\theta)$, DR production
- First order condition for $\hat{\theta}^*$ given a, b, s, and q: $0 \in \partial J(\hat{\theta}^*)$, $\Leftrightarrow$

$$MC(\hat{\theta}^*) = \begin{cases} a & \text{if } DR(s) + s > q \quad \text{(overproduction)} \\ b & \text{if } DR(s) + s < q \quad \text{(underproduction)} \end{cases}$$

and $DR(s) + s = q \Leftrightarrow MC(DR^{-1}(s)) \in [a,b]$: zero imbalance, if marginal cost of required DR is between the imbalance prices

Contingent Optimal DR Procurement (Monopsony/Olinopsony solution)



(a) Optimization of marginal type.

(b) Optimization of DR quantity.

Putting it all Together

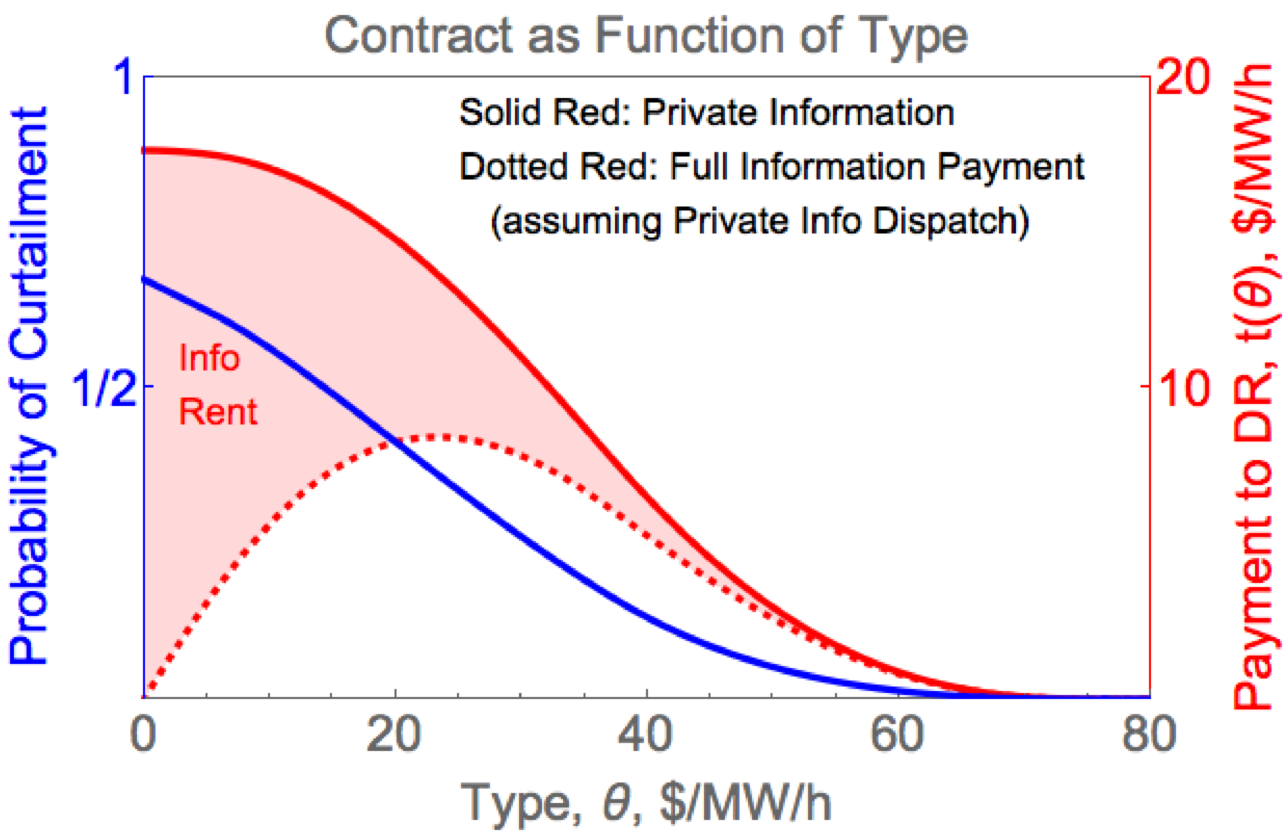
1. Aggregator determines curtailment policy in each (p, a, b, s), given q: $\text{MC}(\hat{\theta}^*) = \text{MB}(\hat{\theta}^*)$
2. For each (p, a, b) choose q^* so that the $\mathbb{E}[\text{MC}(\hat{\theta}^*)]$ above $= p$
3. $q : (p, a, b) \mapsto q(p, a, b)$ is a supply surface: contingent offer policy
4. Taking expectation over (p, a, b, s), these elements determine $\kappa(\theta) = \mathbb{E}[\Pr\{\theta \leq \hat{\theta}^*\}]$, which determines $t(\theta)$
5. Evaluating $\big(\kappa(\theta), t(\theta)\big)$ for each $\theta \in [\underline{\theta}, \overline{\theta}]$, we get the explicit menu ("indirect mechanism"), mapping κ's to t's

Simple Example

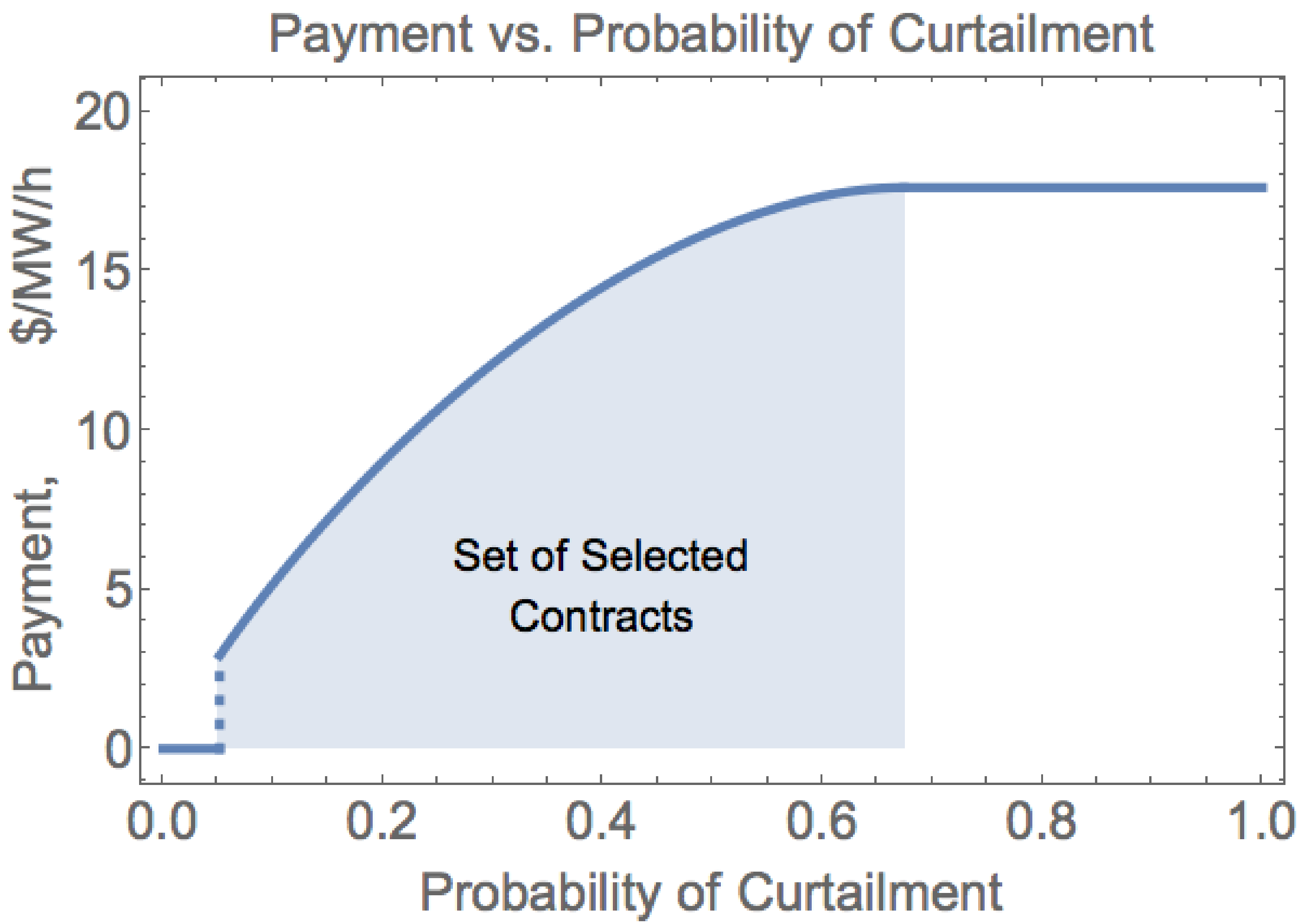
$$\overline{s} = 100 \text{ MW}$$
$$R = \$30/\text{MW} \quad \text{(generation component of the retail price)}$$
$$N = D(R) = 100 \text{ MW} \quad \text{(aggregate demand at } R = \$30)$$
$$\eta(R) = 0.3 \quad \text{(elasticity at } R = \$30)\,.$$

$$p \sim \text{Uniform}[10, 100]$$
$$a = (1 - \delta)p$$
$$b = (1 + \delta)p$$
$$\delta \sim \text{Uniform}[0.1, 0.9]\,.$$

Target Contract Terms as Function of Type

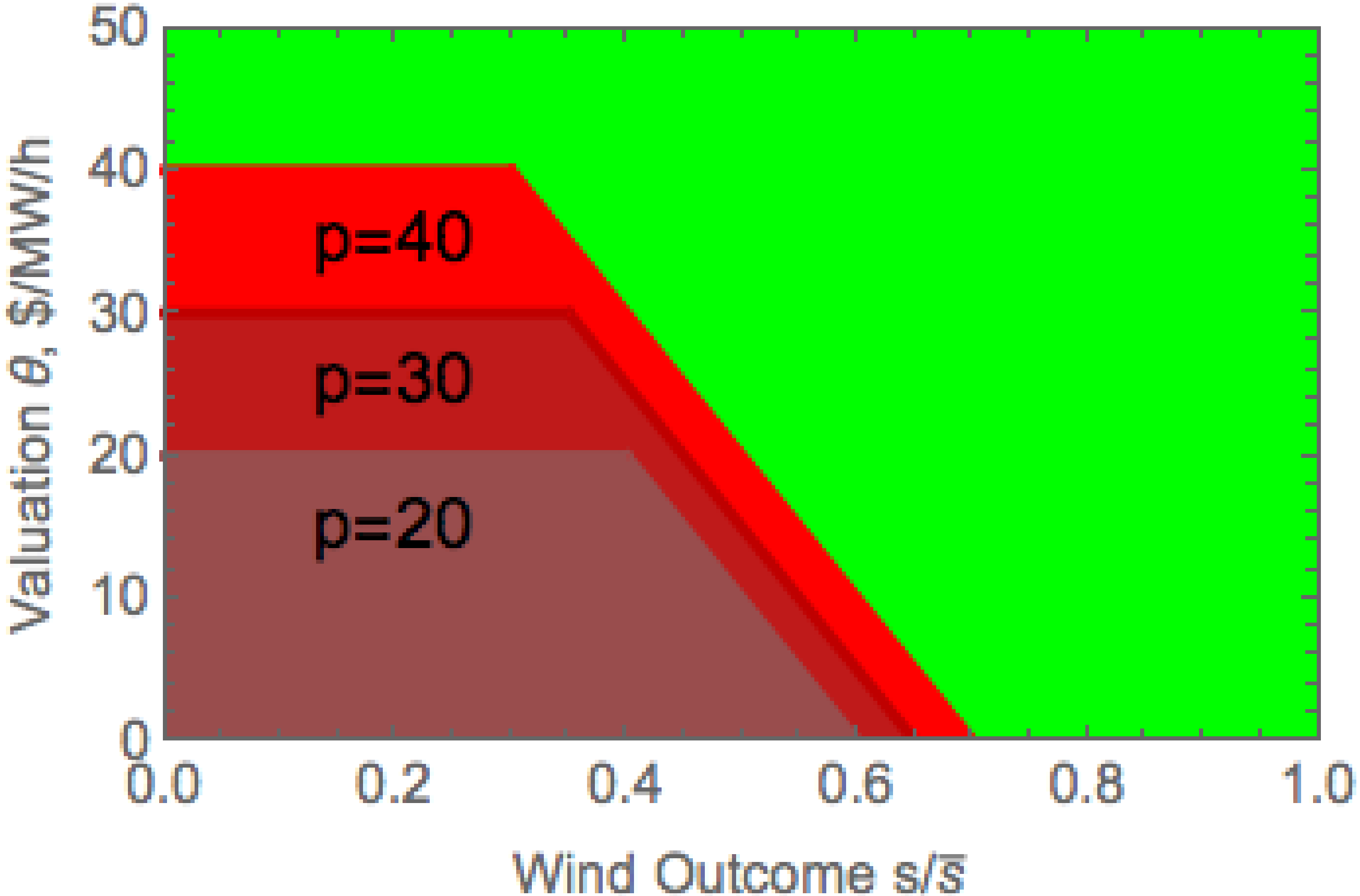


Payment to DR as Function of Curtailment Probability

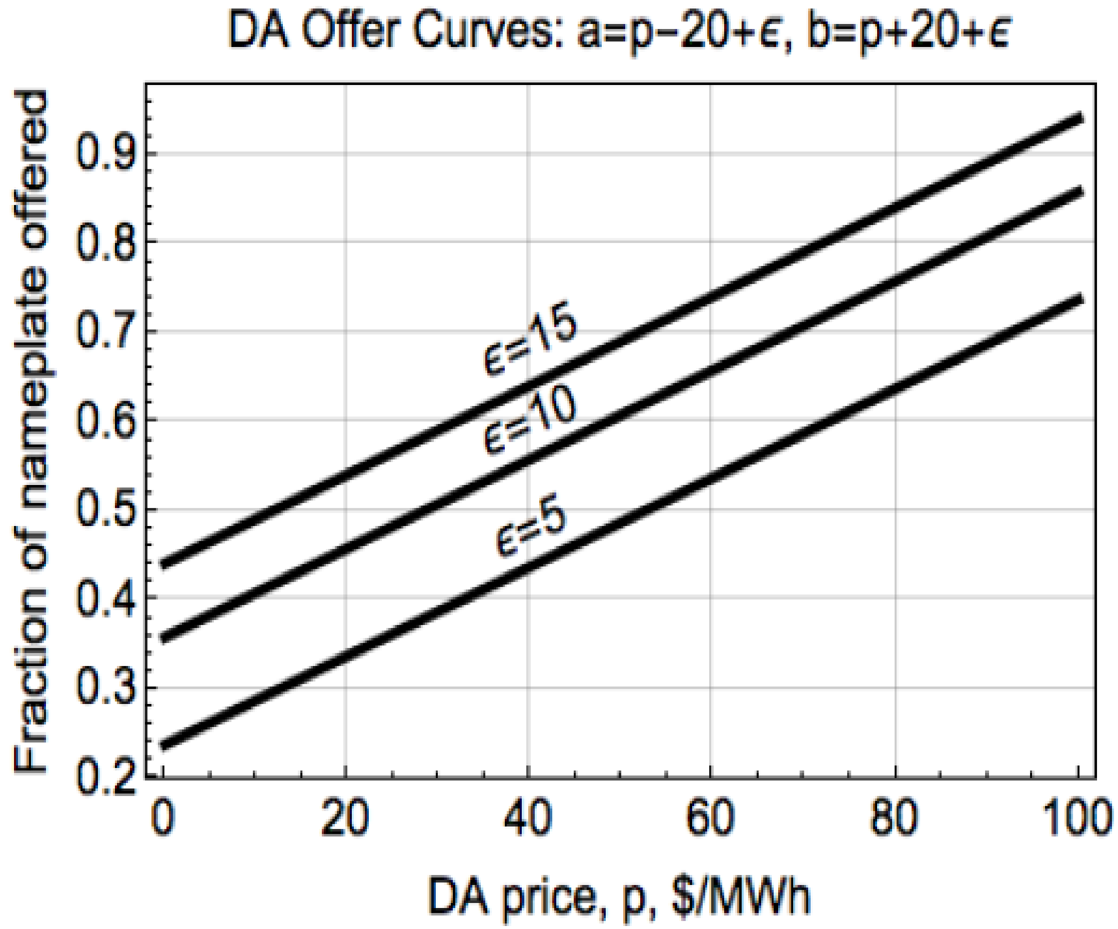


Optimal Curtailment Policy

(for *a=0, b=2p*)



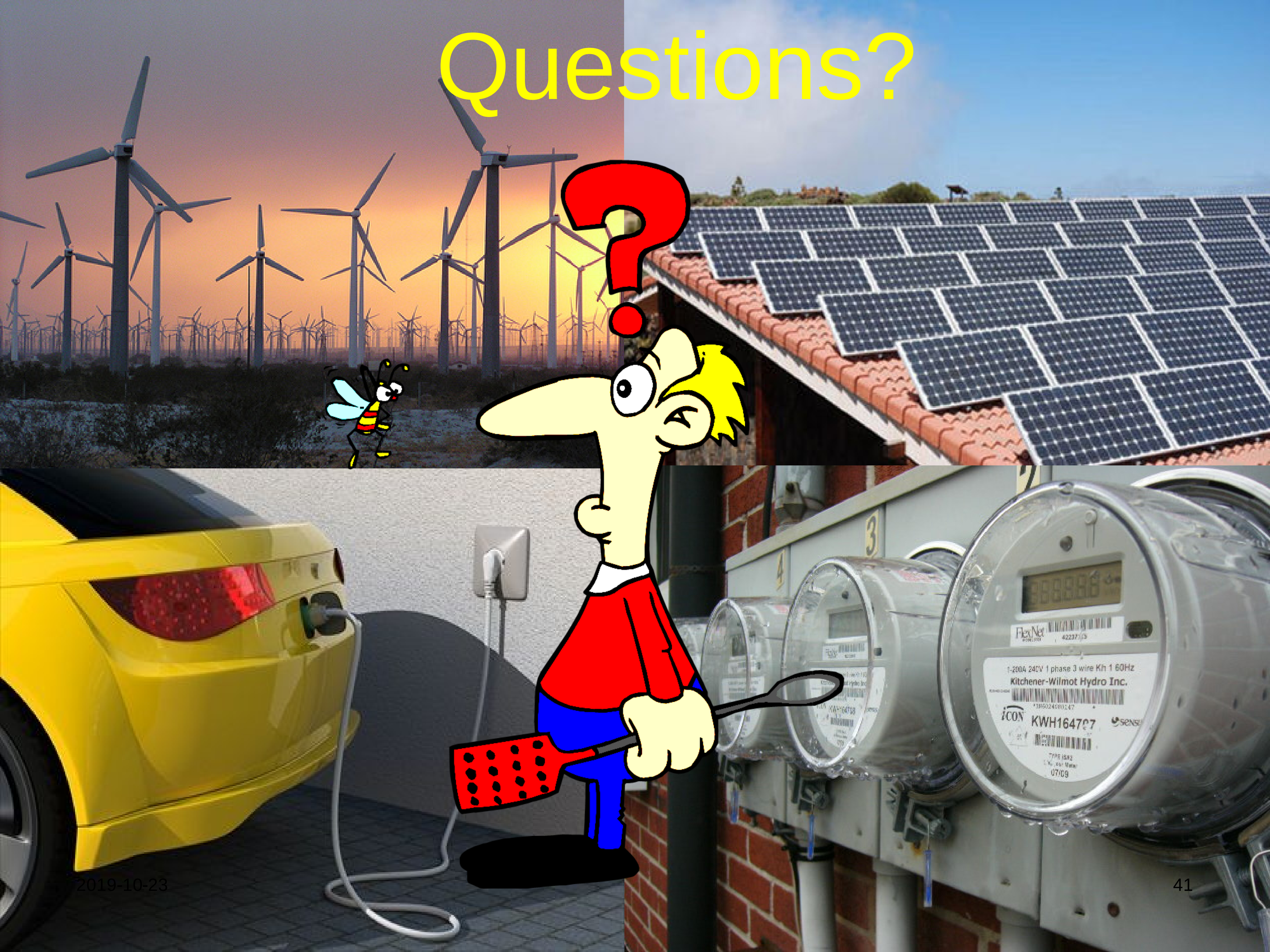
Supply Functions



PUBLICATIONS & PRESENTATIONS

- Oren Shmuel S., “A Historical Perspective and Business Model for Load Response Aggregation Based on Priority Service”, Proceedings of the 46th HICSS Conference, Maui, Hawaii January 7-10, pp 2206-2214, 2013.
- Margellos, Kostas and Shmuel Oren, “Capacity Controlled Demand Side Management: A Stochastic Pricing Analysis”, IEEE PES Transactions, Vol 31, No 1, (2016) pp 706-717.
- Margellos Kostas and Shmuel Oren, “A Fuse Control Paradigm for Demand Side Management: Formulation and Stochastic Pricing Analysis”, Proceedings of the American Control Conference , Chicago, Ill, July 1-3, 2015.
- Campaign Clay and Shmuel Oren, “Firming Renewable Power with Demand Response: An End to End Aggregator Business Model”, Journal of Regulatory Economics, Vol 50, No. 1, (2016), pp. 1-37.

Questions?


1-200A 240V 1 phase 3 wire Kh 1 60Hz
Kitchener-Wilmot Hydro Inc.